[redacted]

ARR June 1941

[redacted]

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

June 1941 as
Advance Restricted Report

A FLIGHT INVESTIGATION OF THE THERMAL PROPERTIES OF AN EXHAUST HEATED WING DE-ICING SYSTEM ON A LOCKHEED 12-A AIRPLANE

By Lewis A. Rodert and Lawrence A. Clousing

Ames Aeronautical Laboratory
Moffett Field, California

NACA

WASHINGTON

A-45

A FLIGHT INVESTIGATION OF THE THERMAL PROPERTIES OF AN EXHAUST HEATED WING DE-ICING SYSTEM ON A LOCKHEED 12-A AIRPLANE

By Lewis A. Rodert and Lawrence A. Clousing

SUMMARY

The thermal properties are presented for the exhaust heated wing de-icing system of a Lockheed 12-A airplane which has successfully prevented wing icing in 25 hours of flying in various icing conditions. The quantities of heat supplied for de-icing of the wings under various conditions were measured and are presented. The distribution of temperatures above the ambient air temperature for the wing surface under various operating conditions are given. The design and construction of the wing heating system are described and design factors relative to the weight, maintenance, and the applicability to exhaust heating on other airplanes are discussed.

INTRODUCTION

In a recent confidential report (reference 1), an investigation was described in which a Lockheed 12-A airplane equipped with exhaust-heated wings was flown in icing conditions to determine the extent of ice protection which could be afforded by the thermal method. As noted in reference 1, and further substantiated in more recent flights, the heating system employed on the test airplane provided adequate protection against ice formations on the wing surfaces. In the present investigation, the quantity of heat employed in the ice-prevention system and the manner in which the heat was distributed over the wing surface were determined. Information on additional topics which will be of interest to designers such as added weight, corrosion data, thermal-expansion and structure-temperature data, maintenance problems, effects on performance, and notes on the operation of the system, have been obtained and are reported.

The tests were made in flight in the vicinity of Moffett Field, California, from the Ames Aeronautical Laboratory of the National Advisory Committee for Aeronautics. The observations relative to the maintenance and overhaul of the ice prevention system have been made with the benefit of the experience obtained from 131 hours' flight time, of which approximately 25 hours have been in icing conditions.

The heat-exchange system employed for the prevention of ice on the airplane wing was designed from data taken from references 2, 3, and 4. Information from reference 2 indicated the quantity of heat which would be required for raising the surface temperature of the wing a given amount, and reference 3 suggested approximately to what temperature the surface should be raised in dry air in order to de-ice the wing during icing conditions. Reference 4 gives the basis for calculating the transfer of heat from the exhaust gas to the exhaust tube, from the tube to the air in the leading edge, from the air to the wing skin, and from the tube to the wing surface by radiation. In the investigation reported in reference 5, the validity of the calculations for the design was experimentally examined by model tests in simulated icing conditions. Preliminary to undertaking the alterations to the test airplane, consultations were had with representatives of the Army Air Corps, the Navy Bureau of Aeronautics, air transport companies, airplane manufacturers, and other technical experts in order to obtain a complete coverage of competent opinion on the design.

EQUIPMENT

A description of the equipment employed in the investigation was given in reference 1, but is repeated and somewhat expanded in the present report. The test airplane, shown in figure 1, is a Lockheed 12-A commercial transport airplane, equipped with two Pratt & Whitney, 450-horsepower, Wasp Junior engines, and 8-foot, 10-inch diameter, constant-speed propellers. The wings are heated by the passage of all or part of the engine exhaust gas through wing exhaust tubes which are installed along the wing leading-edge interior. The degree of heating and, to some degree, the distribution of the heat are controlled from the pilot's cockpit. The principal elements which comprise the wing heating system are shown in figure 2. Heat from the exhaust gas which flows along the wing tube is transmitted to the tube wall and thence to the wing structure as a result of (1) convection and conduction through the air in the leading edge, and (2) radiation from the tube wall. The circulation of air through the wing interior, the path of which is shown in figure 2, is controlled by a valve at the air inlet. A baffle plate, extending from the wing root to tip, directs the flow of air along the leading edge. Figure 3 shows the heated wing in section, with the important structural components noted. The baffle plate serves also as a front shear web, and, in effect, a fire wall in the event that any leakage developes in the exhaust tube. The circulation of air through the wing serves other purposes in addition to the heat-transfer function. The passage of air along the wing leading edge is intended to prevent structural parts near the exhaust tube from being overheated, and to prevent the accumulation of corrosive, explosive, or poisonous gas in the wing interior.

The pilot's controls for the wing heating system are shown in figure 4. The exhaust tail pipe and exhaust control valves are shown in figure 5. A clapper-type valve over the normal discharge of the exhaust closes simultaneously with the opening of a butterfly valve in the wing heating tube elbow. A choice of eleven positions of this valve system is provided. When the control is in the "off" position, all of the exhaust is discharged directly to the atmosphere; and when in the "full-on" position, all of the exhaust is passed through the wing. Surface orifices and thermocouples are provided in the exhaust tail pipe and exhaust collector, by which pressure and temperature measurements are made. The exhaust tail pipe is constructed from 0.050-inch-thick stainless steel. A double-ball universal joint between the tail pipe and the wing exhaust tube is employed to allow for motion due to vibration and thermal expansion.

Figure 6 shows the center-section wing leading edge, looking inboard toward the engine nacelle with the leading edge beyond the wing joint removed. The inboard end of the wing leading edge is shown in figure 7. The wing tube is unrestrained from spanwise movement within the wing except at the inboard end ball joint. Chordwise restraint and support are provided at several rib stations along the span. The types of construction of the tube supports at rib stations are shown in figures 8 and 9. The coil springs and mounting rings are made of inconel; most ribs and leading-edge skin are of aluminum. The ribs in the leading edge at the tip stations are made of inconel; the support clips are of stainless steel. At all points along the wing exhaust tube where restraint is provided, the tube is reinforced to prevent abrasion at these points from causing a rupture in the tube wall and subsequent gas leakage.

The discharge end of the wing exhaust tube is shown in figure 10. It will be noted from a comparison of figures 7 and 10 that the wing exhaust tube is tapered from the wing root to the wing tip. At the wing root, the tube is circular with a 5-inch diameter; and at the tip, the tube is elliptical, the major and the minor axis being 4.75 and 2 inches, respectively. The tip end of the tube protrudes through the wing-tip rib and is free to expand linearly when heated. The discharge of exhaust gas from the wing tube is into the tip shroud, shown in figure 11. The shroud is constructed from inconel. The tip skin near the shroud and the forward shear web to which the shroud is attached are made of stainless steel. No provision was made for thermal expansion in the wing-tip construction.

The parts of the exhaust tube are assembled in such a manner that each part can be removed independently of the remaining system. The tail pipe and the wing tube elbow are removable without removing the wing or the wing leading edge, and the wing leading edge and the wing tube are removable without disturbing the inboard end of the exhaust system. The wing tube is removable from the leading-edge structure.

Drain holes are made in the lower wing surface to provide for the removal of water taken in with the circulating air. The interior surface of the wing leading edge is treated with zinc chromate primer, a corrosion-resistant paint. Although it was noted in the analysis of the heating system that the transfer of heat by radiation would be increased by treating the exterior of the wing exhaust tube and the interior of the wing leading edge with a black paint, no special treatment was applied to these surfaces. Future tests will be made to investigate the effect of black surfaces on the heat transfer in the wing.

The exterior of the wing surface along the leading edge was made as smooth as possible. It was also noted in the analysis of the heating system that the quantity of heat required for a given surface temperature rise was reduced by preserving laminar flow. To this end, flush rivets were used and skin joints avoided over the leading-edge surface.

The weight of the wing heating system was found to be about 100 pounds, which is about 1.1 percent of the airplane weight.

The temperatures of the heated wing skin, critical structural parts, circulated air, and the engine exhaust gas were recorded by the use of thermocouples. The position of the thermocouples and the object of temperature measurement are given in figure 12. The engine exhaust-gas temperature was measured at three points in the collector ring, in the tail pipe, in the entrance to wing heating tube, and in the discharge of the exhaust at the wing tip. The temperature of the airplane structure was measured at two points in the main wing beam, at a typical rib in the leading edge, at two points in the wing baffle, and at one point in a protective shroud near the wing-center section joint. The circulating air temperature was measured at five points. The temperature of the upper and lower wing covering was measured at 13 points, ten on the upper and three on the lower surface. The thermopotentials were recorded by the use of two millivoltmeters and a photorecorder. Recorded simultaneously with the potentials of the thermocouples were the altitude, air speed, air temperature, and time.

A water-filled U-tube manometer was used to measure the back pressure in the exhaust manifold which resulted from passing the exhaust gas through the wing duct. The flight instruments normally used in the Lockheed 12-A airplane were employed to record observed flight and engine data.

TESTS

The flights during which the heat-exchange data were taken followed the investigation in inclement weather, the results of which are reported in reference 1. As described in reference 1, ice was prevented from forming on the wing surfaces by the use of the heating system. Figure 13 demonstrates the protection afforded by the heating system, showing the leading edge of the wing after a flight in severe icing conditions. The small tell-tale strut mounted above the wing shows the ice formation which remained on this part after the flight.

With the knowledge that ice prevention was effective, the heat-exchange tests herein described were made to determine the amount of heat supplied to the wing surface by the exhaust gas under various operating conditions, and the variations in the temperature of the wing due to variations in engine power and air speed, air-fuel ratio, air circulation through the wing, and atmospheric conditions. Most of the flights were made in dry air - that is, air free from clouds. The object in conducting the thermal investigations in dry air is to provide data on a proven ice-prevention system, comparisons to which can be made by airplane manufacturers without recourse to inclement weather tests. One flight was made in an altostratus cloud during which icing conditions were encountered.

RESULTS AND DISCUSSION

Thermal design.- The numerical data obtained in the present investigation are given in tables I and II. Table I gives the pertinent flight data and the distribution of the heat from one engine. The purpose in presenting these data is to reveal approximately the thermal values involved in the exhaust heating system. The difficulty of measuring the exhaust-gas temperature and calculating the rate of flow is recognized and the possibility of errors in the order of 10 percent is acknowledged. Table II gives the temperatures measured in the wing heating system. Actual temperatures are given; but in the design of a wing heating system it should be noted that the difference between the air temperature and the heated wing temperature, which can be computed from the table, is important. Attention is directed to the index notes in table II which give the variations in the heating conditions.

Figure 14 shows graphically the results of one test which is given numerically in table I. Figure 15 shows graphically the temperature rise over the wing surface at three chord stations and for three flight conditions. The temperature-rise curves in figure 15 are faired from thermocouple data in the vicinity of the wing stations shown. The data in figures 14 and 15 are typical test results.

The heat supplied to the wing was influenced only slightly by changes in fuel-air ratio. While the temperature of the exhaust gases is greater for lean mixtures, the transfer of heat to the wing surface was greater during flights with rich mixtures, other factors remaining the same. The circulation of air through the wing increases the quantity of heat delivered to the wing surface but disrupts the temperature uniformity, as will be noted below. The heat delivered to the wing surface increases with increase in power, and therefore normally increases with speed. It is of interest to note that, with increasing speed, the loss of heat from the wing does not increase as fast as does the heat supply from the engine, as demonstrated by the higher surface temperatures at the highest test speeds. The full power of the engines was never reached during the tests, although the maximum allowable cruising power, of 300 horsepower, was approached in tests 11 and 12 during which 288 horsepower was employed.

As a generalization from the test results, it may be stated that the temperature of the forward 20 percent of the heated wing surface is raised approximately 70° F above the air-stream temperature. The temperature rise of the wing surface between the 20-percent and 70-percent chord points varies from about 70° F at the forward station to less than 10° F. at and in rear of the rear station. The temperatures along the span are highest at the wing tip. The temperature of the leading-edge skin near the air inlet (see fig. 2) approaches the air temperature when circulating air is admitted. When the air valve is closed, the temperature of the leading edge is uniform along the span. A change in the air circulation system is planned whereby circulation may be provided and the temperature along the span maintained uniform. This will be done by taking the circulating air into the wing at a point on the lower surface of the wing and nearer to the engine nacelle.

The small temperature rise along the trailing edge results in temperatures slightly below freezing for this region when air temperatures in the vicinity of 20° F are encountered. During flights in icing conditions,(reported in reference 1) and at air temperatures below 20° F, thin films of ice were observed to form at scattered points on the wing surface near the trailing edge. These formations have never exceeded 1/8-inch in thickness and are not considered serious. Protrusions or surface roughness of small dimensions in the region of the trailing edge cannot produce a serious effect upon either the lift or drag of the wing.

The danger of ice forming on the after portion of the wing is small, because, during conditions when a large quantity of condensed moisture is present in the air, the air temperature is high; and it has been observed that even a small surface temperature rise will prevent ice accretion. When the air temperature is low in the icing range, the quantity of condensed moisture is small; the drop sizes are very small; and little water makes contact with the wing at the leading edge, less near the trailing edge.

The rate of ice formation and the frequency of icing storms are greatest at air temperatures in the vicinity of 26° F; under these conditions the temperature rise required for ice protection is small as shown by icing tests. During one icing flight the heat control was placed in the "off" position for a period to determine if, when turned on again, ice could be removed. With the control in the "off" position, sufficient gas leaked past the exhaust valve to prevent the formation of ice. The air temperature during this test was 27° F. The temperature rise of the wing surface with the heat turned off was about 20° F as shown by test 6, table I. It is suggested that, when greater experience has been obtained in the operation of aircraft in icing conditions, the temperature rise possible with the heating system tested will be considered greater than necessary for protection in ice storms within the United States region.

The temperature rise which is required for ice protection is determined by the temperature range of icing storms in which operations are anticipated. As the air temperature decreases the total amount of water in the air, the quantity of condensed water in the air, and the drop size become smaller. In consideration of small water content, a calculation of the heat required for ice protection at very low temperatures may be made on the basis of dry-air heat-transfer data. It will be noted by way of illustration that tests 13 and 14 (see table II), which were made in icing conditions, gave substantially the same temperature rise of the surface as was obtained during dry-air tests. Also during an ice prevention test in moderate icing conditions, the results of which are shown in figure 21 of reference 1, the wing surface temperatures along the wing leading edge were found to be over 60° F above the air-stream temperature, which was at 0° F when the measurements were recorded. Reference 5, table II, however, indicates that the presence of water in the atmosphere, in large quantities such as may be found at temperatures in the vicinity of 32° F, alters the heat transfer coefficient by about 25 percent of the dry-air coefficient. Thus while the larger quantities of water present in the air at temperatures near 32° F will prevent the same temperature rise as obtained in dry air, this is unimportant for design considerations inasmuch as the design conditions will be the provision of protection at air temperatures below 0° F, the heat for which may be calculated on the basis of dry air transfer coefficients.

The protected wing area of one heated wing panel is approximately 100 square feet, and the total heated area per semispan is 200 square feet since both upper and lower surfaces must be considered. The quantity of heat per square foot supplied to the wing as obtained by dividing the total values given in table I by 200 is found to vary from 664 Btu/sq ft, hr at 118 miles per hour to 1280 Btu/sq ft, hr at 170 miles per hour, indicated air speeds. The values of heat supplied thus are found to be in close agreement with the thermal data given in table III, reference 5. The value of 1300 Btu/sq ft, hr as given in table II, reference 5 is probably a safe and conservative figure to use, but it should be noted that the velocity and scale of the airplane must be considered, as will be discussed later. Since successful ice prevention was obtained on several flights during which only a part of the full heating capacity of the wing was employed, it is believed that future experience will demonstrate that deicing is possible with 1000 Btu/sq ft, hr.

Structural considerations.- The temperatures in the wing structure which result from the use of the exhaust heating system as shown in table II are not excessive. The structures on which thermocouples at 1B, 2B, and 3B were located were made of heat- and corrosion-resistant steel, as it was anticipated that these would be the hottest structural members. Since the strength of aluminum alloys is not seriously affected by temperatures under 300° F, all of the wing structure could have been made of aluminum with the exception of the baffles and shrouds near the nacelle end of the exhaust tube. The temperature of the exhaust tube near the tip is low (under 400° F), and therefore aluminum parts are not in danger of overheating if a small air gap is provided between all parts and the tube. The temperature of the main beam, rib flanges, stringers, and all other primary structural parts did not exceed 150° F. The materials used for the heated wing structure and the duct system is believed to be satisfactory for practical application. Owing to the need for corrosion resistance, the use of stainless steel will be found justified at some points not having a large temperature rise. In the vicinity of the wing tip, exhaust gas leakage resulted in excessive corrosion of the aluminum skin after 120 hours' service. The defective plates were replaced with stainless steel. A change that is to be made in the design of the tip shroud will eliminate the gas leakage. For the main wing structure, any material that is satisfactory at temperatures resulting from exposure to a bright summer sun will be suitable for a heated wing.

The double-ball joint between the wing tube and tail pipe has been found satisfactory. The double flanged elbow in the tail pipe (see fig. 5) allows a slight exhaust gas leakage, and when first put in service, several bolts were broken due to expansion. The gas leakage in the region of the elbow was counteracted by shrouding this section of the exhaust tube and venting the shroud to the air stream. The breaking of bolts is believed to have been due, in part, to initial tension, since, by not drawing the flange bolts down tight, further breakage has been avoided.

Vibrations in the semi-elliptical tip shroud (see fig. 11) caused a crack along the leading edge at the discharge end. Three stiffeners, which appear as vanes in the end of the shroud, were installed which prevented reoccurrence of this failure.

Some gas leakage into the wing leading edge at the wing tip has also been observed. A scheme for the solution of this problem has been in operation for an insufficient time to determine whether the method is satisfactory. Continued attention is being given all maintenance problems related to the heated wing.

Performance.- The back pressure in the exhaust collector ring due to the passage of the gas through the wing tube was found to be insufficient to produce any measurable effect on the performance of the engines. The greatest back pressure measured was $7\frac{1}{2}$ inches of water, as given in table I. It seems probable that even this amount could be reduced by permitting the exhaust to follow a more direct path from the engine collector ring to the wing tube. Since the present installation was the result of alterations to an airplane already built, the most direct path was very difficult to obtain, and the present structure was chosen as a compromise. The installation and operation of the heating system has had no effect upon the performance, control, or stability of the airplane.

It may be of interest to note that the efficiency of a heated wing de-icing system should be greater when applied to a low-drag wing inasmuch as the heat transfer coefficient decreases with the decreased skin friction coefficient, as discussed in reference 7, and consequently, there is less heat loss to the outside air.

Applicability of exhaust heating.- The series of investigations conducted by the National Advisory Committee for Aeronautics have demonstrated that heat from the engine exhaust gas can be delivered to the airplane wing surface in sufficient quantity and with sufficient uniformity to provide reliable ice protection. The investigation has indicated the magnitudes of the thermal values involved in the design of one full-scale heating system. The provision of wing heating in the design of an airplane obviously involves some penalties the magnitude of which, evaluated in relation to the protection to be obtained, should determine the type of installation.

If it has been decided that an airplane is to operate extensively in inclement weather and is to be exposed often, and during long flights, to icing conditions then in consideration of the need for high aerodynamic efficiency the costs of wing heating appear to be small compared to the protection and other advantages which are obtained. The aerodynamic effects of other de-icing means are reported in reference 6.

An expression containing the factors which are involved in the design of the exhaust wing heating system has been developed by equating the power required in level flight to the heat dissipation, and is given as follows:

$$\Delta T = 1.15\ R\ \frac{\rho V^3\ (C_D + KC_L{}^2)}{\frac{\lambda_m}{l}\,\psi\left(\frac{l V_o\ \rho_m}{\mu_m}\right)} + \frac{V^2}{2\ JgC_p}$$

where

ΔT practicable wing surface temperature rise, degrees F

R ratio of wing heating to thrust power

ρ air density, $lb\text{-}sec^2/ft^4$

V velocity, ft/sec

C_D profile drag coefficient of complete airplane

C_L lift coefficient

K a function of aspect ratio

J mechanical equivalent of heat, ft-lbs/Btu

g acceleration of gravity, ft/sec^2

C_p specific heat of air at constant pressure Btu/lb, degrees F

The function $\frac{\lambda_m}{l}\,\psi\left(\frac{lV_o\ \rho_m}{\mu_m}\right)$ is defined in reference 2, and represents the heat transfer coefficient α.

The expression for ΔT indicates that, in general, for modern commercial and military airplanes, the temperature rise varies as follows:

(a) ΔT increases with velocity.

(b) ΔT increases with size.

The effect of aerodynamic heating is expressed in the function $\frac{V^2}{2\ JgC_p}$ which was developed from reference 8 and investigated in reference 9. Increasing the velocity <u>increases</u> the capacity to heat because the thrust power increases more rapidly than the surface heat loss, and <u>decreases</u> the need for heating because of the effect of aerodynamic heating.

Increasing the size of the protected body not only reduces the heat transfer coefficient, but also reduces the ratio of the number of water drops which make contact with the wing to the number of drops in the swept air volume (reference 10).

In summary, the disadvantages in the application of exhaust heating are not great. The weight increase, based on the experimental installation in the Lockheed 12-A airplane, will probably vary between 1/2 and 1½ percent of the total airplane weight. The diversion of exhaust gas from supercharging or ejector stacks may be avoided by the use of other heat sources, or a compromise made by using only a part of the engine exhaust gas heat for ice protection, the remainder for augmenting the thrust. The complication in maintenance and cost of maintenance will probably be less than that in other widely used ice-protecting devices.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif.

REFERENCES

1. Ródert, Lewis A., McAvoy, William H., and Clousing, Lawrence A.: Preliminary Report on Flight Tests of an Airplane Having Exhaust-Heated Wings. NACA confidential report, 1941.

2. Theodorsen, Theodore, and Clay, William C.: Ice Prevention on Aircraft by Means of Engine Exhaust Heat and a Technical Study of Heat Transmission from a Clark Y Airfoil. Rep. No. 403, NACA, 1931.

3. Rodert, Lewis A.: A Preliminary Study of the Prevention of Ice on Aircraft by the Use of Engine-Exhaust Heat. T.N. No. 712, NACA, 1939.

4. McAdams, William H.: Heat Transmission. McGraw-Hill Book Co., Inc., 1933.

5. Rodert, Lewis A., and Jones, Alun R.: A Flight Investigation of Exhaust-Heat De-icing. T.N. No. 783, NACA, 1940.

6. Rodert, Lewis A., and Jones, Alun R.: Profile-Drag Investigation of an Airplane Wing Equipped with Rubber Inflatable De-icer. NACA confidential report, 1939.

7. von Kármán, Th.: The Analogy Between Fluid Friction and Heat Transfer, Trans. A.S.M.E., vol. 61, no. 8, Nov. 1939, pp. 705-10.

8. Brun, Edmond: Distribution of Temperature Over an Airplane Wing with Reference to the Phenomena of Ice Formation. T.M. No. 883, NACA, 1938.

9. Rodert, Lewis A.: The Effects of Aerodynamic Heating on Ice Formations on Airplane Propellers. T.N. No. 799, NACA, 1941.

10. Kantrowitz, Arthur: Aerodynamic Heating and the Deflection of Drops by an Obstacle in an Air Stream in Relation to Aircraft Icing. T.N. No. 779, NACA, 1940.

TABLE I

Engine data and calculations of heat distribution.

THE CALCULATIONS ARE FOR ONE ENGINE AND ONE WING.

Test No.	Airspeed Mph (indicated)	Alt., feet	Air temp. °F	Man. Press., in. Hg	Fuel-air ratio	Engine speed, Rpm	Engine Bhp	Exhaust gas, lb/hr
1	113	6400	42	18.0	0.076	2000	151	1640
2	118	6350	41	18.4	0.076	2000	156	1670
3	165	6700	42	25.0	0.078	2000	250	2260
4	165	6700	43	25.0	0.079	2000	250	2260
5	140	3750	51	21.0	0.080	2000	186	1920
6	134	7530	40	19.6	0.077	2000	180	1770
7	130	7600	40	19.5	0.083	2000	177	1780
8	123	7500	41	19.5	0.071	2000	178	1775
9	155	7600	43	24.0	0.072	1900	227	2050
10	153	7500	41	24.0	0.093	1900	225	2100
11	170	7400	42	28.7	0.095	1900	288	2410
12	170	7300	44	28.8	0.083	1900	288	2395
13	150	12790	24	23.0	0.072	2000	240	2100
14	125	13150	20	17.8	0.072	2100	181	1700

Test No.	Heat through tail pipe, btu/hr	Heat lost in nacelle, btu/hr	Heat out wing tip, btu/hr	Heat to wing surface, btu/hr	Exhaust back-pressure, in. H_2O	Index No.
1	616,000	186,000	290,000	140,000	2.0	
2	644,000	203,000	308,000	133,000	2.0	
3	796,000	143,000	444,000	209,000	4.5	2
4	826,000	143,000	449,000	234,000	4.5	3
5	733,000	225,000	282,000	226,000	3.0	
6	677,000	---	---	---	0.0	5
7	630,000	92,000	314,000	224,000	3.0	
8	680,000	186,000	356,000	138,000	3.0	
9	820,000	178,000	430,000	212,000	4.6	
10	694,000	146,000	354,000	194,000	5.0	
11	722,000	92,000	374,000	256,000	7.5	
12	920,000	---	---	---	7.5	~~1, 4~~
13	792,000	119,000	419,000	254,000	5.5	1, 4
14	654,000	102,000	337,000	215,000	4.0	

Indices:
1. Refer to figure 14 for graphic illustration.
2. Refer to figure 15 (a) for wing surface temperature rise.
3. Refer to figure 15 (b) for wing surface temperature rise.
4. Refer to figure 15 (c) for wing surface temperature rise.
5. Exhaust discharged through normal port, none through wing.

TABLE II. Temperatures observed in wing heating system.
(The test numbers correspond to those used in table I.)

Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Air- (indicated) speed, mph.	113	118	165	165	140	134	130	123	155	153	170	170	150	125
Thermocouple location:	Temperatures, °F													
Exhaust gas:														
1A	--	1467	1373	1373	1425	1390	1360	1421	1459	1214	1085	1367	1276	1446
2A	1371	1372	1322	1323	1375	1360	1210	1411	1364	1129	1085	1267	1326	1306
3A	1416	1422	1372	1373	1425	1410	1360	1361	1459	1367	1215	462	1471	1426
4A	1136	1162	1322	1323	1140	1195	1125	1126	1314	1129	1130	1317	1426	1426
5A	1001	1002	1137	1138	1005	660	990	1036	1129	994	995	1132	1196	1186
6A	696	722	812	773	585	360	660	761	764	664	615	--	776	751
Structure:														
1B	181	182	247	248	195	10	195	236	264	214	265	--	141	--
2B	218	184	213	250	224	109	201	217	269	246	241	--	271	239
3B	346	316	377	120	293	114	288	292	282	277	209	--	305	302
4B	111	82	80	125	126	54	103	110	124	118	97	--	98	92
5B	109	80	84	116	118	63	106	110	146	108	108	--	111	103
6B	98	191	178	64	75	45	76	99	64	58	68	--	62	81
Circulating air:														
1C	106	150	213	106	126	92	150	158	159	142	143	154	79	186
2C	--	236	287	268	251	116	234	254	272	242	243	264	268	266
3C	268	--	174	278	140	128	--	155	295	266	116	289	302	--
4C	70	74	96	76	61	43	48	56	33	58	53	59	59	51
5C	74	72	77	64	69	54	64	69	36	61	56	59	62	59
Wing surface:														
1D	101	107	100	99	97	60	89	102	96	89	92	99	84	90
2D	106	101	97	112	110	60	101	107	113	99	111	118	101	106
3D	114	--	115	116	80	63	--	83	119	94	--	123	114	--
4D	87	82	66	--	--	48	43	69	89	80	97	102	74	73
5D	100	82	94	119	116	60	98	69	118	107	114	123	114	92
6D	62	52	55	59	69	46	54	58	64	50	60	--	49	44
7D	51	47	46	48	55	40	44	49	50	42	42	--	37	34
8D	73	80	75	67	75	46	65	77	67	64	65	--	56	56
9D	79	66	69	83	88	51	74	77	89	70	79	--	79	67
10D	165	155	194	127	135	82	141	170	140	129	121	--	157	79
11D'	84	70	77	78	89	54	80	86	86	79	75	--	81	79
12D'	56	50	49	50	58	40	48	55	53	47	48	--	45	42
13D'	53	47	43	67	66	46	57	58	67	58	62	--	56	48
Temperature of air:	42	41	42	43	51	40	40	41	43	42	42	44	24	20
Index number	1	2	2	1	1	3	1	4	4	5	5	1	6	6

Indices:
1. Normal fuel-air ratio, heat and circulating air 'full-on'.
2. Normal fuel-air ratio, heat 'full-on', circulating air off.
3. Wing heat off.
4. Lean fuel-air ratio, heat and circulating air 'full-on'.
5. Rich fuel-air ratio, heat and circulating air 'full-on'.
6. Lean fuel-air ratio, heat and circulating air 'full-on', in icing conditions.

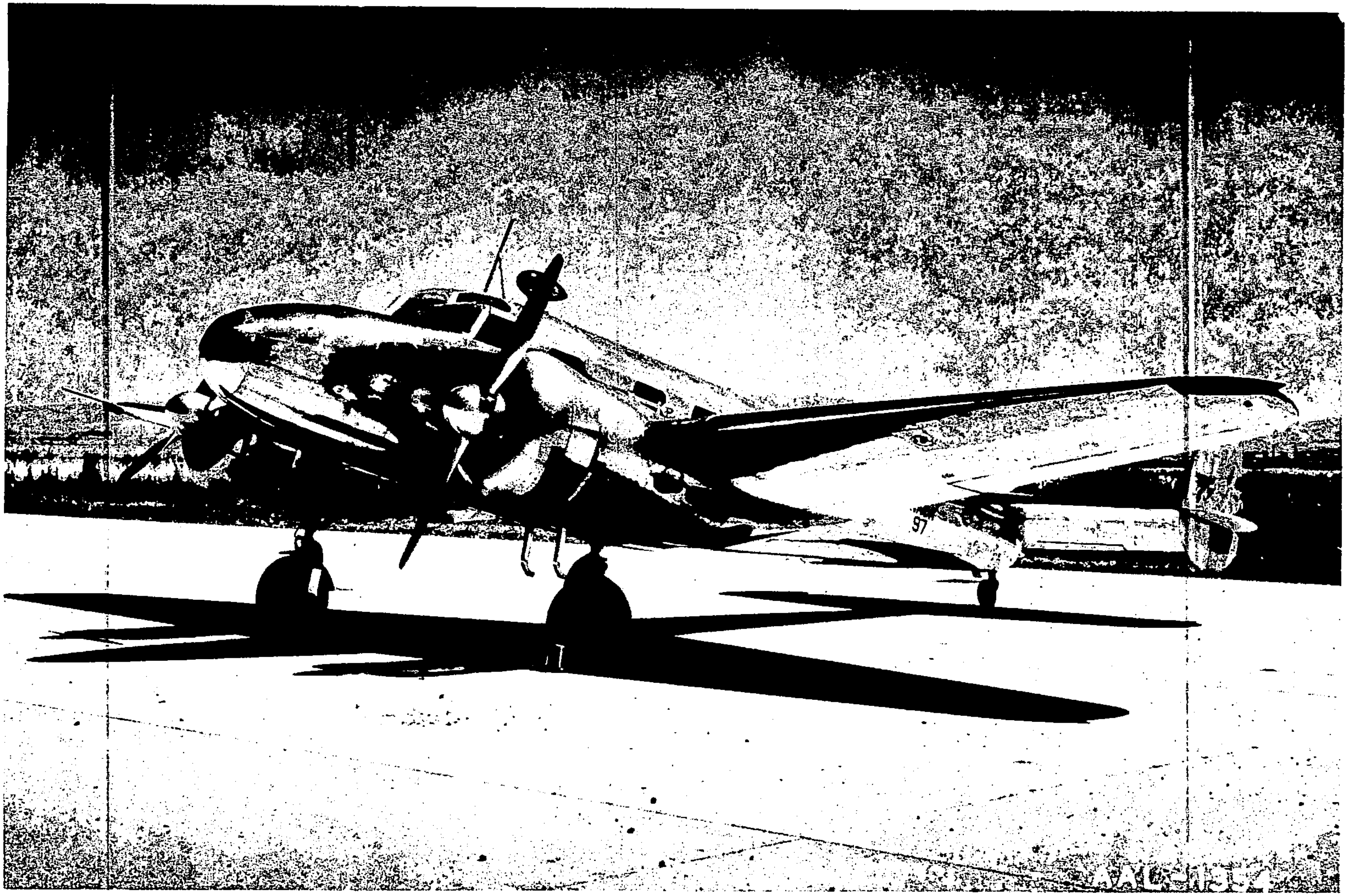


Figure 1.- The Ice Research airplane. A Lockheed 12A commercial transport airplane which has been altered to provide exhaust heating for the wings.

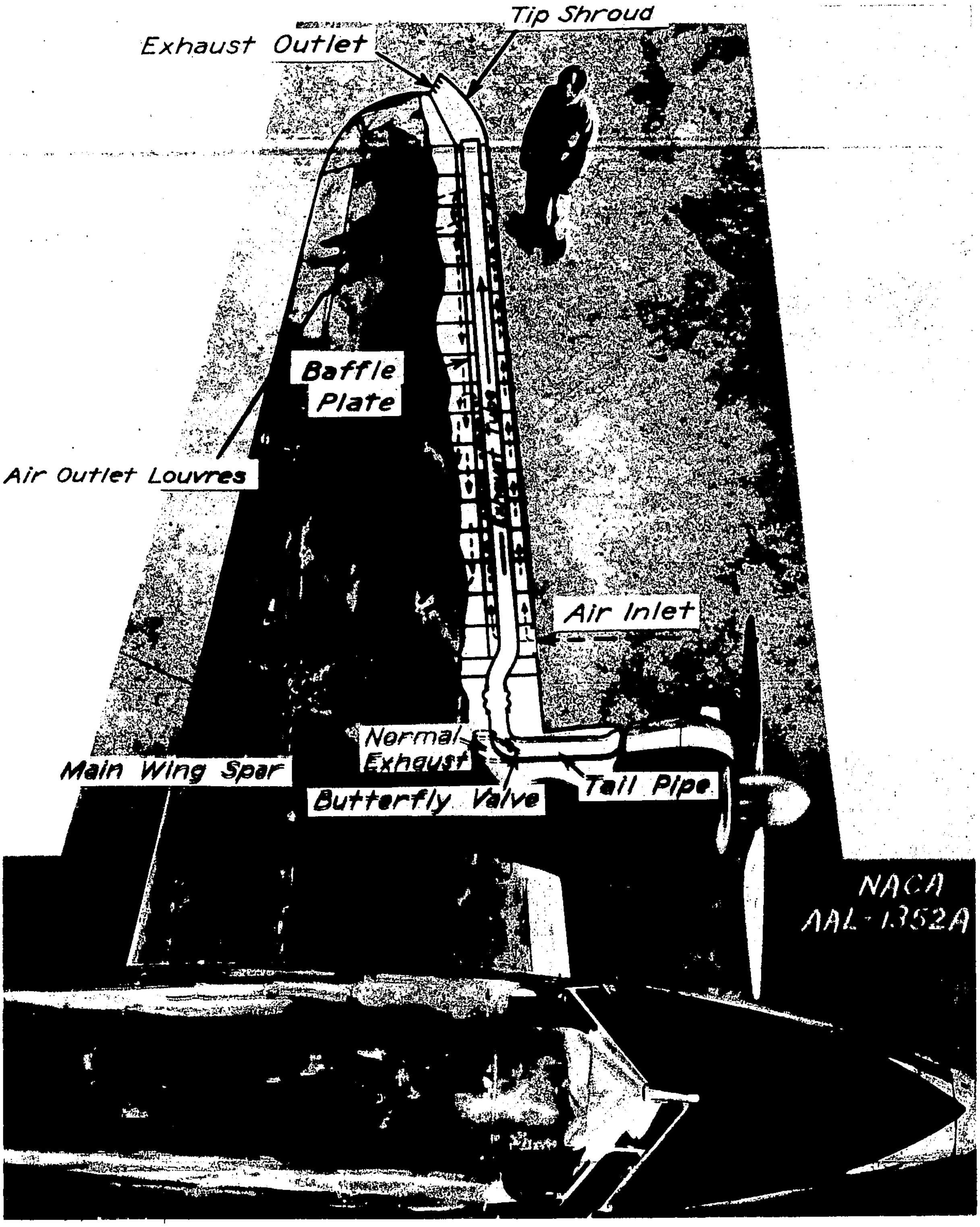


Figure 2.- Exhaust heated wing showing the exhaust tube in the wing leading edge and the path of the circulated air through the wing interior.

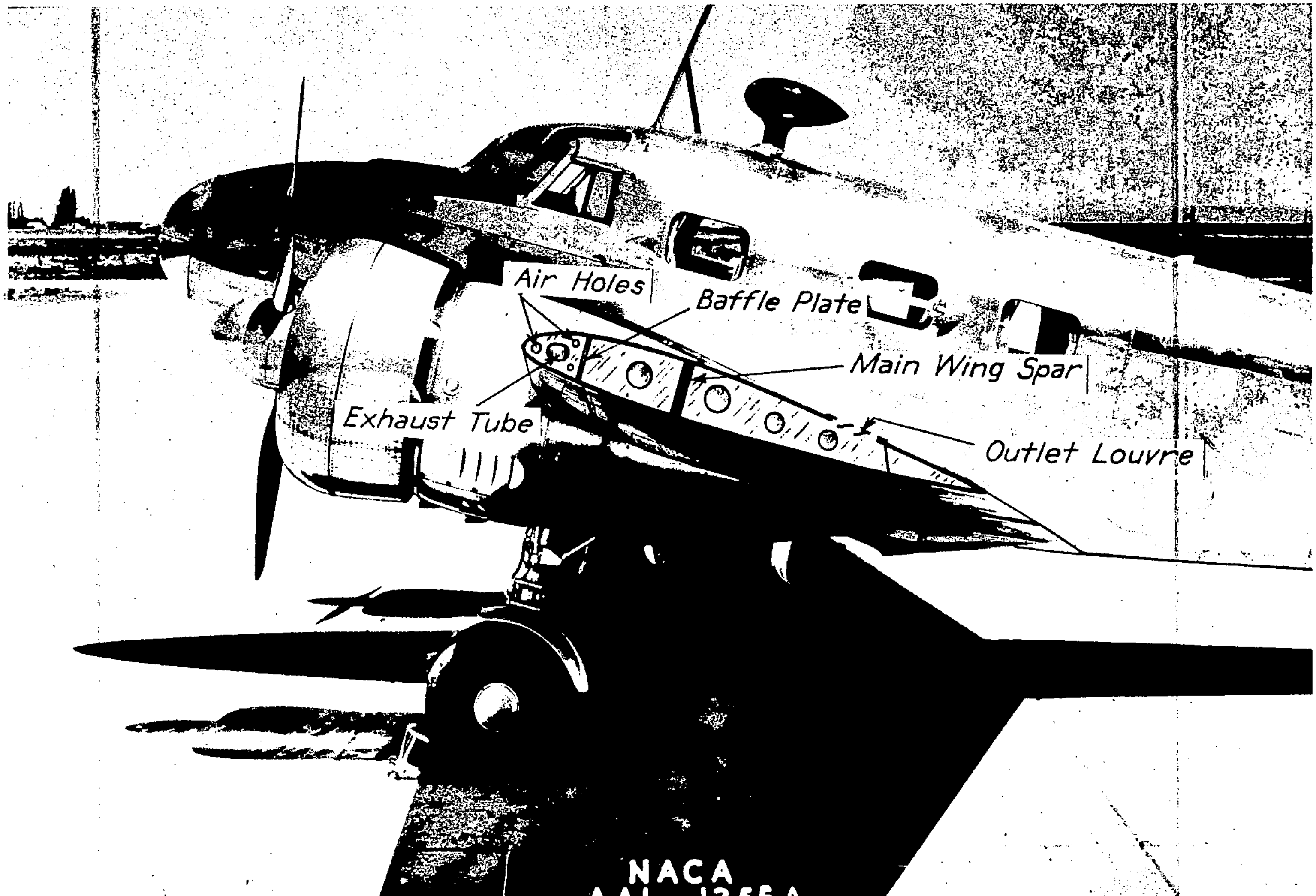


Figure 3.- Section view along a rib of the exhaust heated wing showing the internal structure of the wing and heating system.

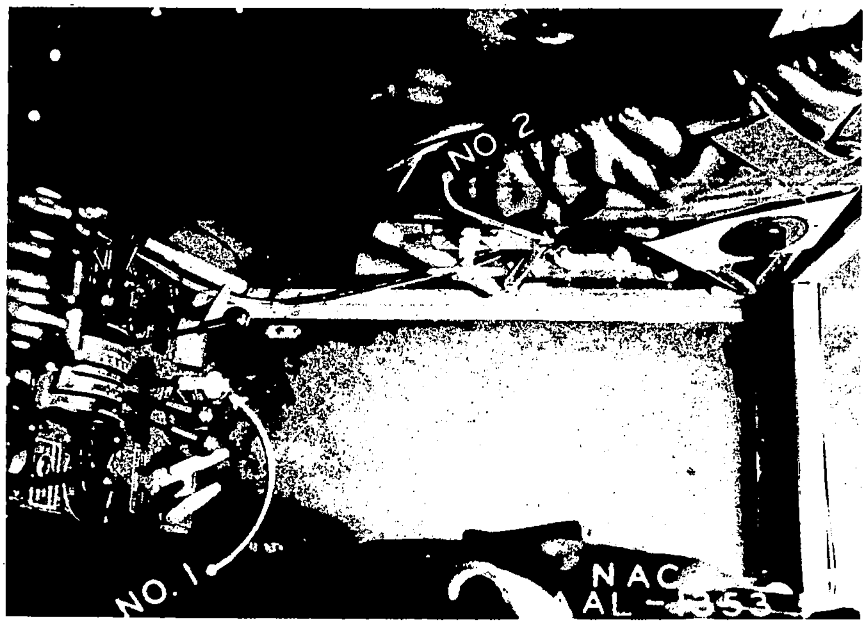


Figure 4.- A view looking downward in the pilots' cockpit showing the heating controls. The control handle marked No.1 is used to vary the quantity of the engines' exhaust passed through the wings, and the handle No.2 varies the quantity of air circulated through the wing interior.

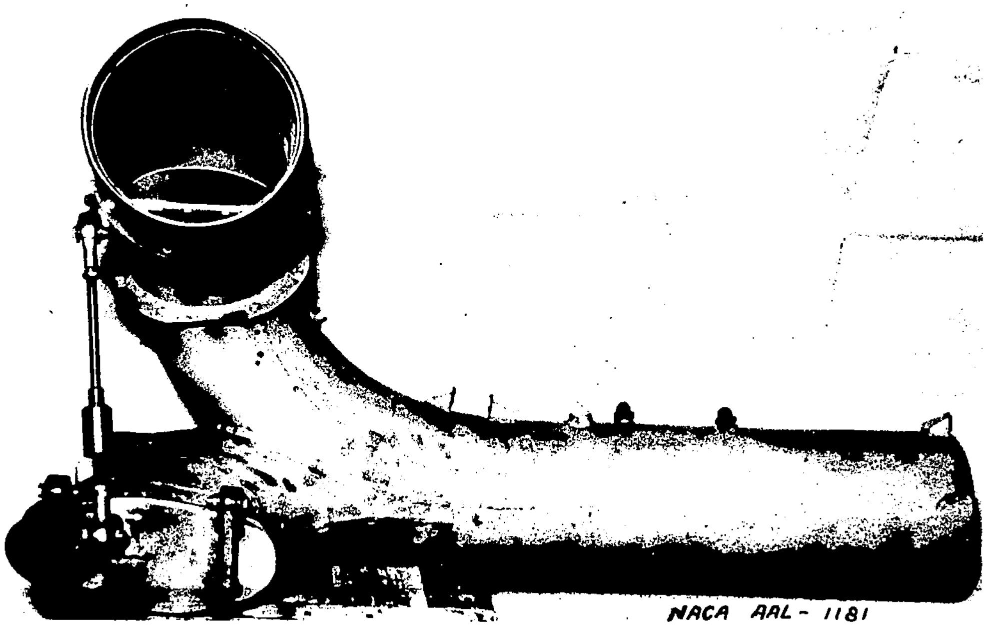


Figure 5.- The exhaust tail pipe and exhaust valve system of the left engine. As the butterfly valve in the elbow opens, the clapper valve over the normal exhaust port closes.

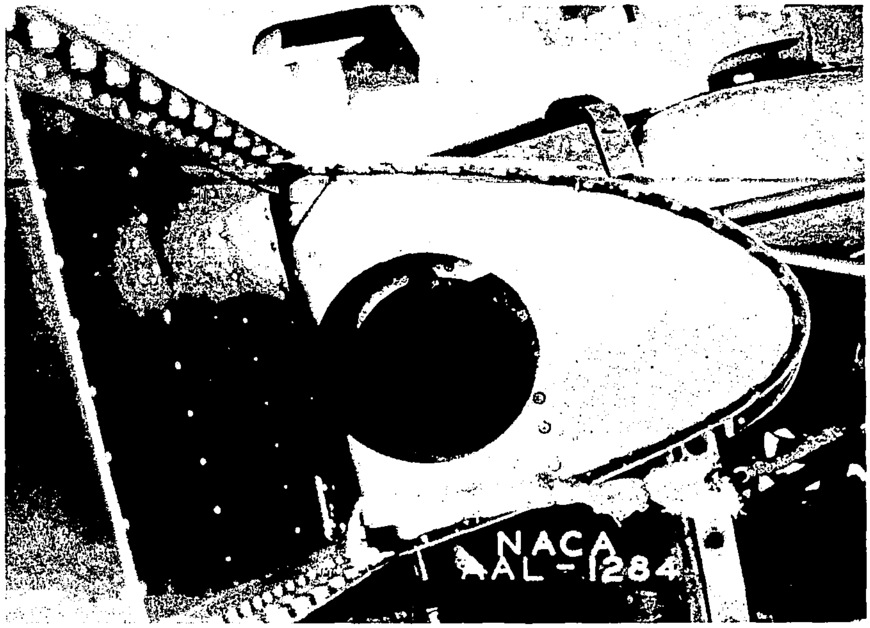


Figure 6.- A view of the wing section at the leading edge and joint between the main wing and center-section. The end of the exhaust tail pipe, to which is attached the wing exhaust tube, is shown.

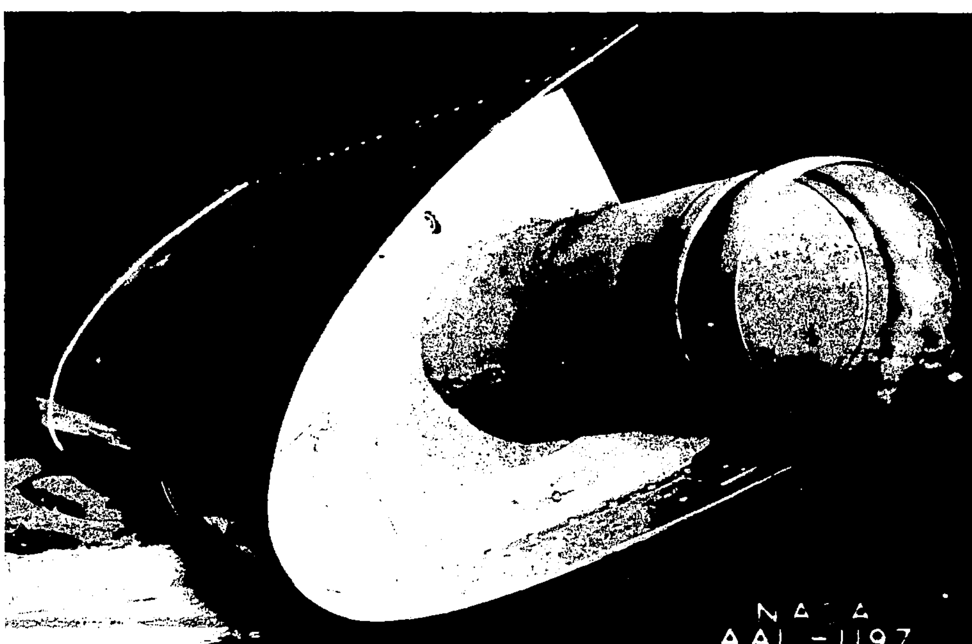


Figure 7.- Heated leading edge of wing showing the inboard end of the wing exhaust tube.

Figure 8.- An interior view of the wing leading edge, the exhaust tube removed, showing the coil spring type of support used at most wing stations where restraint was provided.

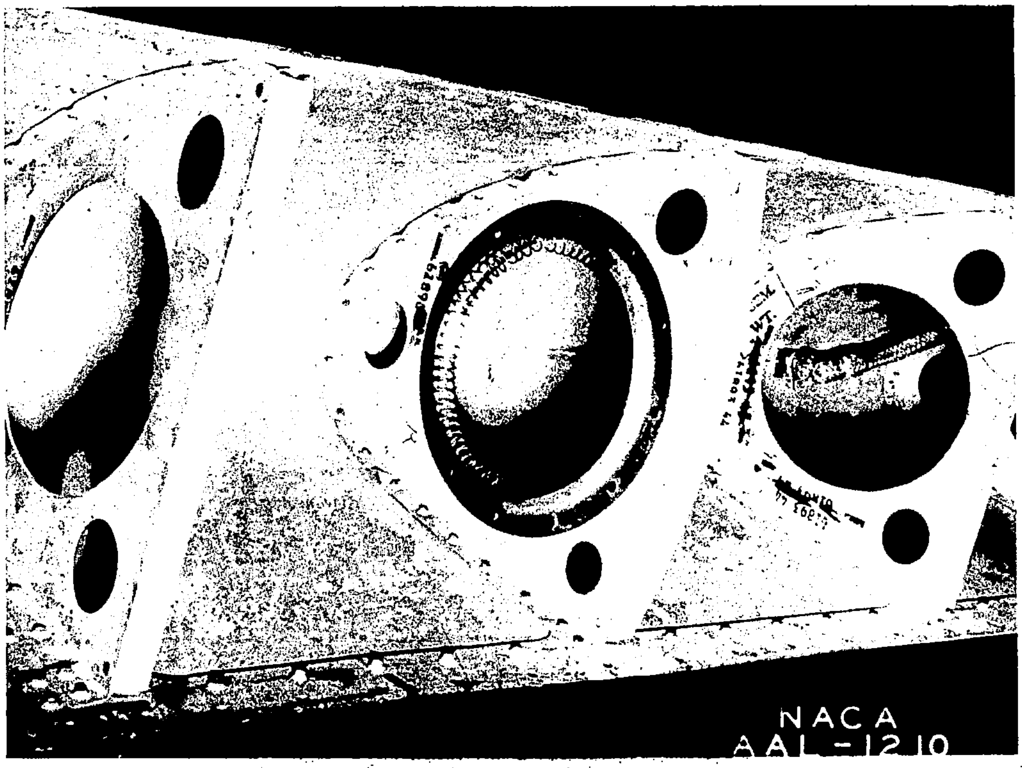


Figure 9.- An interior view of the tip end of the wing leading edge, the exhaust tube removed, showing the clip type support for the tube employed at the tip rib stations where restraint was provided.

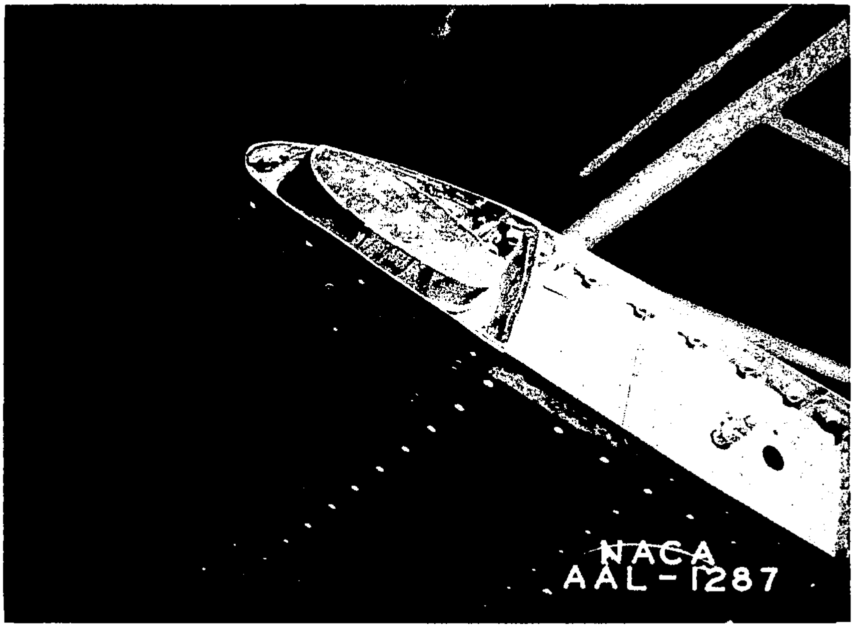


Figure 10.- The heated wing at the tip station showing the discharge end of the exhaust tube. The tube expands through the wing rib when heated.

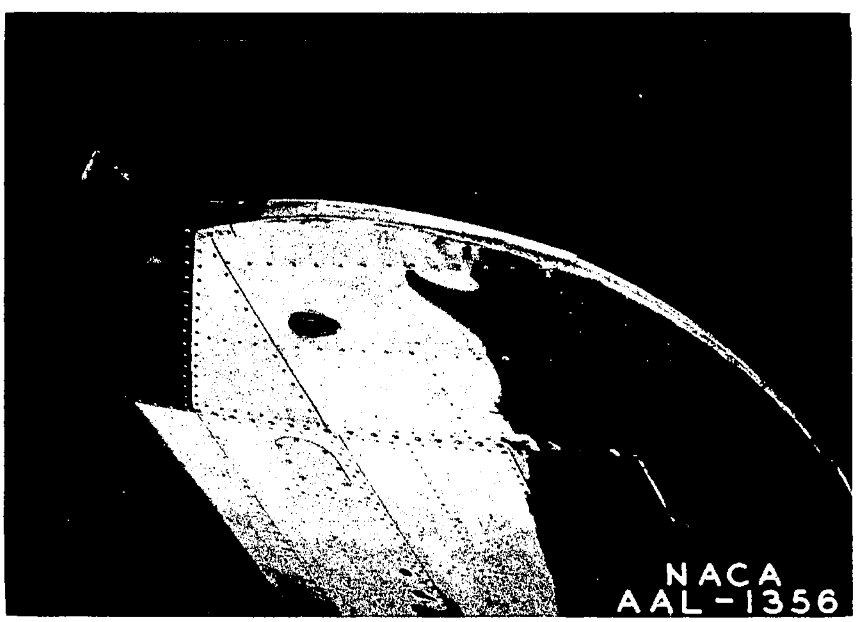


Figure 11.- Exhaust heated wing tip. The exhaust gas is discharged from the wing tube into the leading edge shroud from which it passes to the atmosphere through the opening shown.

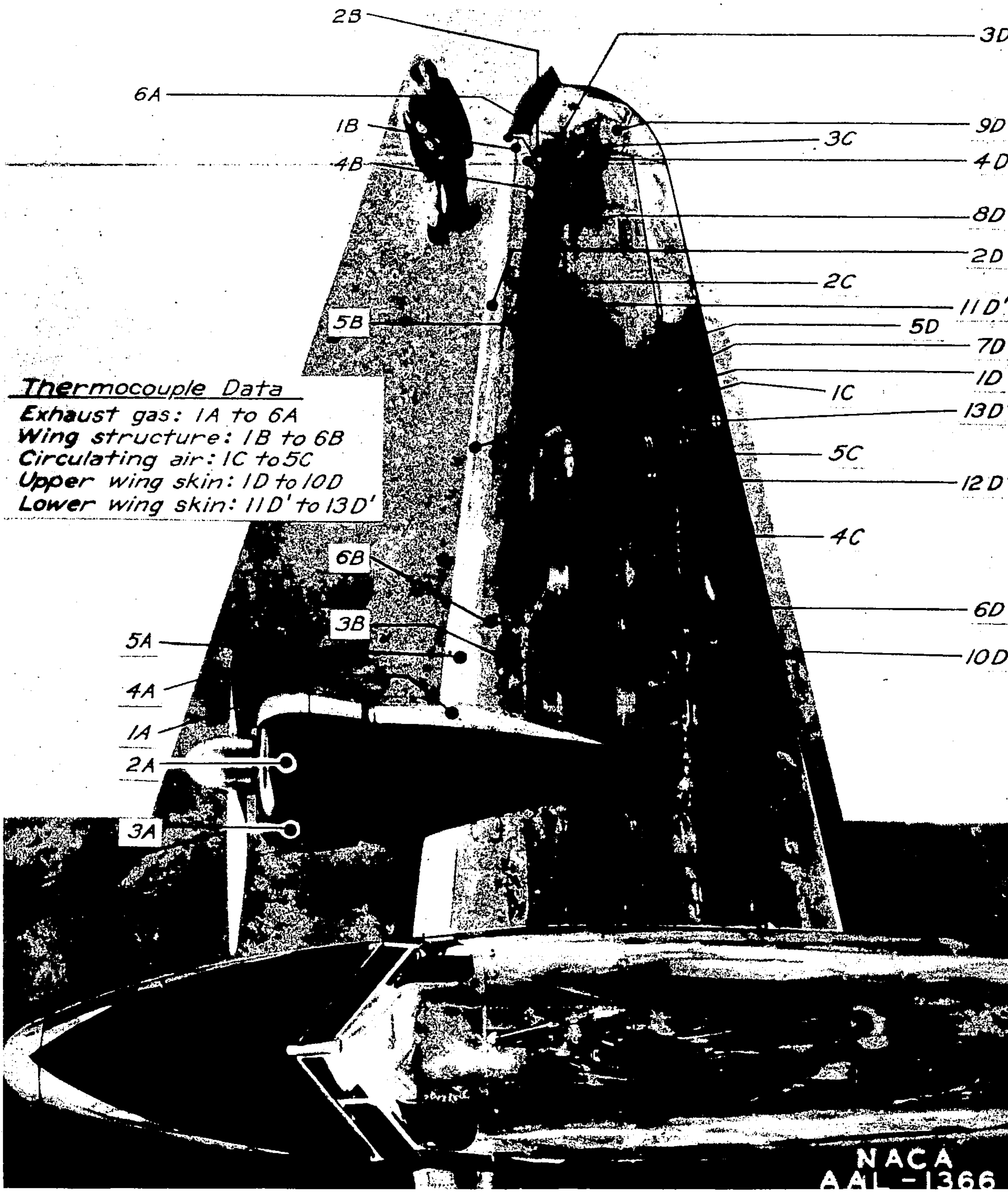
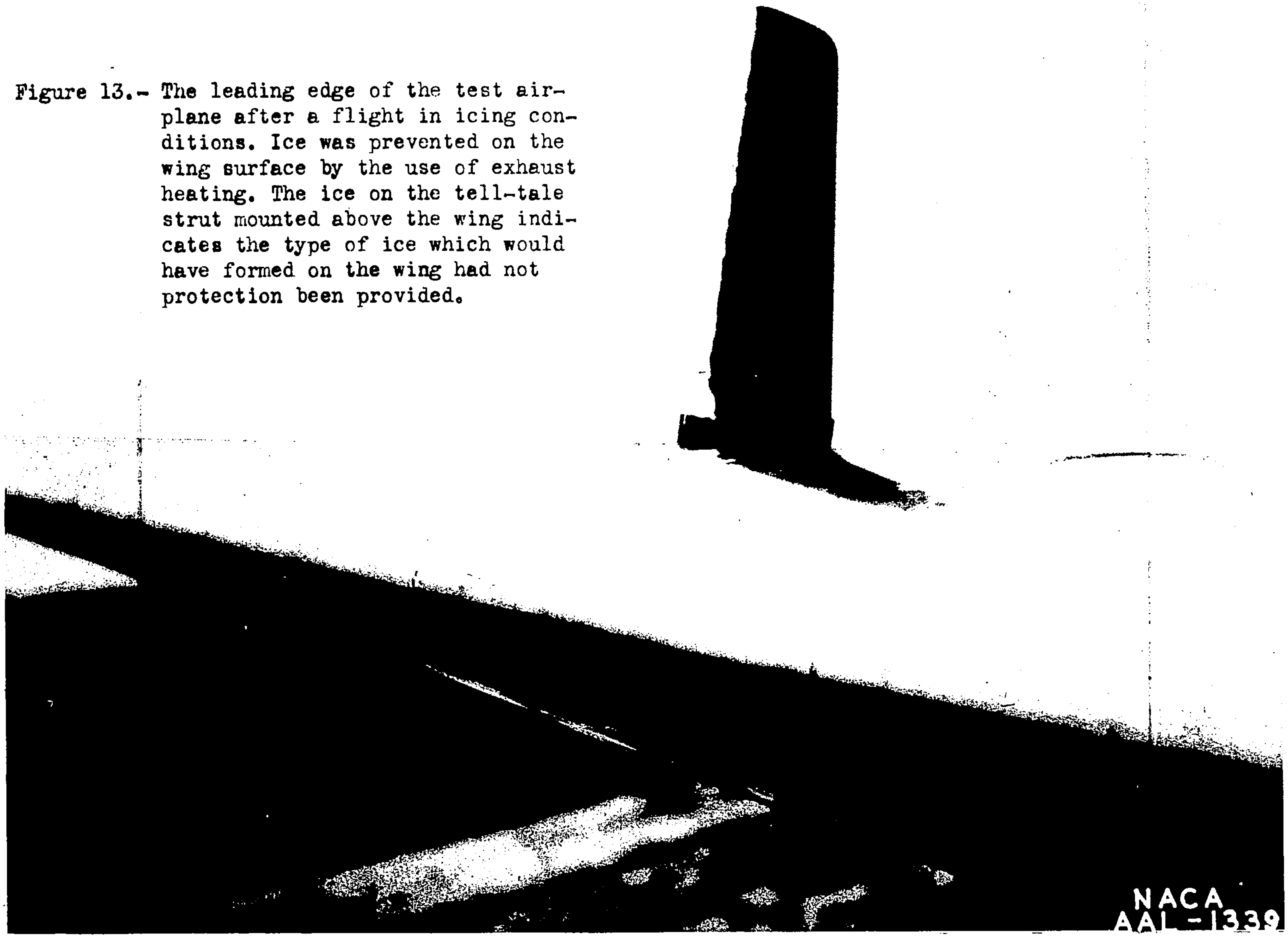


Figure 12.- Thermocouples for measuring the temperature of exhaust gas, structural members, circulating air, and the metal skin of the heated wing.

Figure 13.- The leading edge of the test airplane after a flight in icing conditions. Ice was prevented on the wing surface by the use of exhaust heating. The ice on the tell-tale strut mounted above the wing indicates the type of ice which would have formed on the wing had not protection been provided.



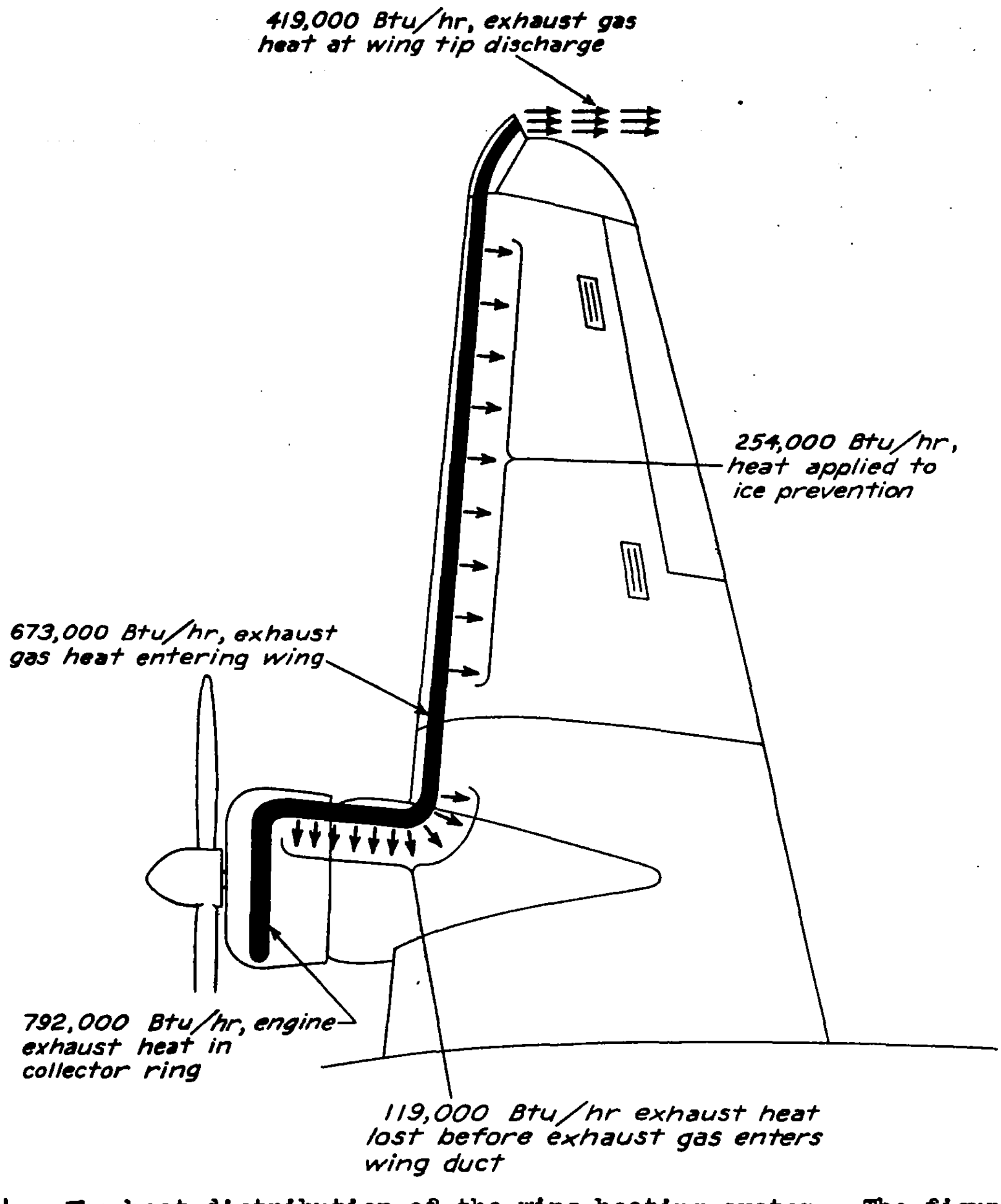
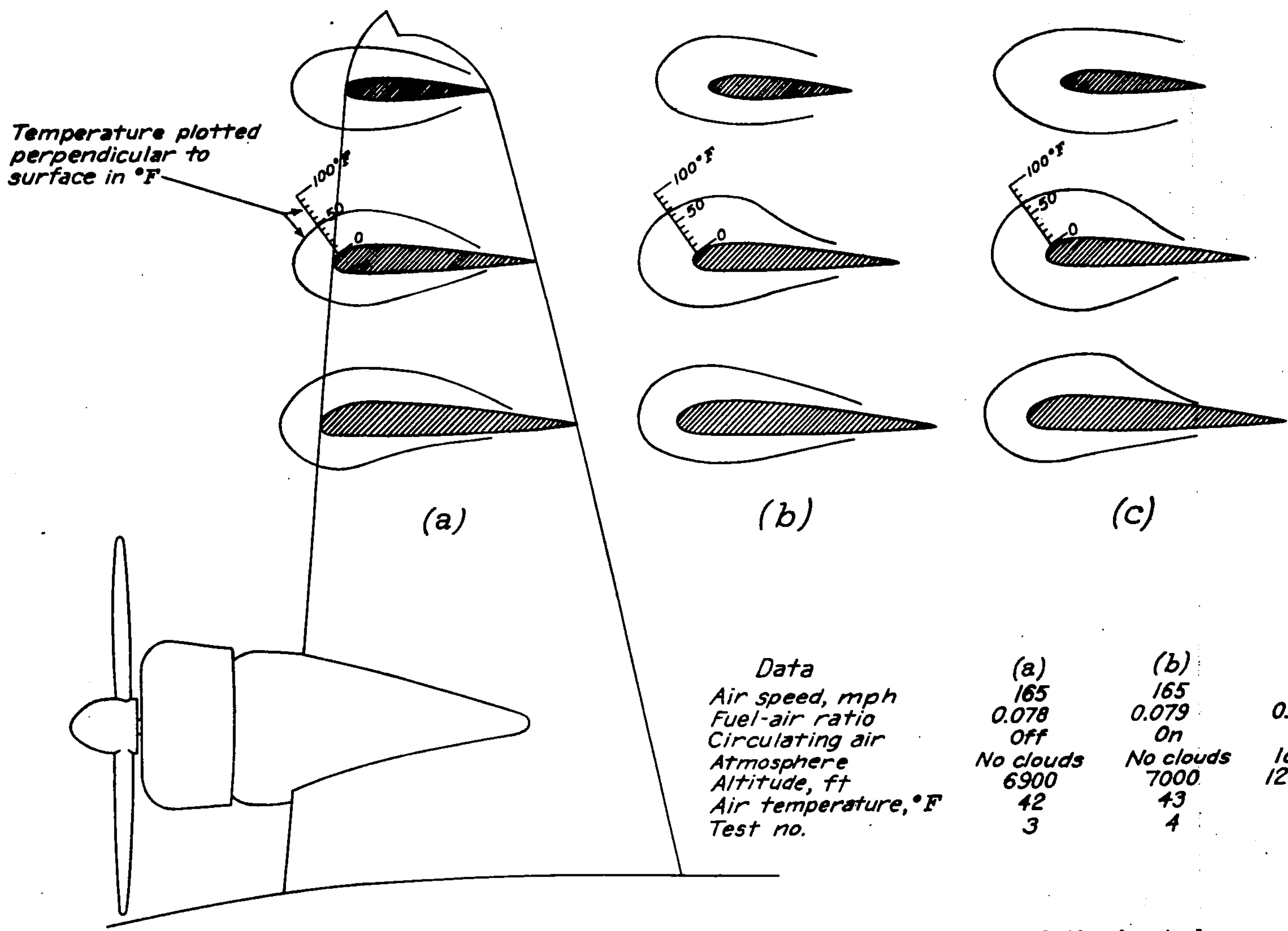


Figure 14. The heat distribution of the wing heating system. The figure illustrates the distribution for the case in which all of the exhaust gas is discharged at the wing tip. See table 1, test No. 13.



Data	(a)	(b)	(c)
Air speed, mph	165	165	150
Fuel-air ratio	0.078	0.079	0.072
Circulating air	Off	On	On
Atmosphere	No clouds	No clouds	Icing
Altitude, ft	6900	7000	12790
Air temperature, °F	42	43	24
Test no.	3	4	13

Figure 15. The temperature rise above air stream temperature of the heated wing surface, showing the results of three typical flight conditions.